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THERMAL PERFORMANCE OF INSULATING WINDOW SYSTEMS

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ABSTRACT

Energy efficient windows coupled with window management strategies can alter the role of windows from that of an energy drain to a net supplier of energy to the building. This will require effective utilization of winter solar gain and daylight, coupled with reductions in thermal losses. Thermal losses of conventional double glazing are less than those of single glass but fall far short of the lower loss rate of other building elements. This paper reviews several improvements in window design, which show promise of reducing the window U value to as low as .5 $W/m^2 \cdot K$ (.1Btu/hr·$ft^2 \cdot {}^oF$). These include the use of: convection suppression in double glazed windows using low conductivity fill gases, with vertical and horizontal partitions; partial evacuation of the air space; transparent heat mirror coatings on glass and on plastic interlayers; movable insulating devices; and air flow windows. Thermal comfort, cost effectiveness and other non-energy related performance issues are discussed briefly relative to several of the proposed designs.

1.0 INTRODUCTION

In a new era of energy conscious building design, much attention has been recently focused on the energy related performance of windows in buildings. The thermal behavior of windows has been extensively studied in the past primarily as an adjunct to the proper sizing of building HVAC equipment. A broader interest has now developed which requires a determination of the net annual energy consumption attributable to windows. This requires the ability to predict interactions and tradeoffs among opposing thermal characteristics as well as between daylighting and thermal performance issues. To properly account for various building level interactions, (e.g., daylighting savings vs. thermal losses), the required analysis must be completed within the context of the overall building performance.

This paper reviews selected technical approaches to reducing energy consumption attributable to windows. Window design and performance has progressed from simple, clear single glazing to high performance fenestration systems. Energy conscious architectural design which utilizes windows effectively in planning the overall building must be based upon the availability of an array of efficient windows and window accessories. We focus here primarily on the heat loss characteristics of improved window systems and components, including both commercially available products which are not widely utilized as well as more speculative approaches which are under development or perhaps deserve additional development, testing, and appraisal. Architectural design issues and non-energy related aspects of window design such as thermal comfort are largely omitted in this discussion. This reflects the limitations of space; we acknowledge the vital importance of those issues in achieving real energy savings.

1.1 BUILDING ENVELOPE DESIGN

Window thermal performance can be viewed from a fundamentally different perspective than that used to analyse opaque building envelope elements. With conventional building elements, a

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reduction in U value reduces both peak thermal losses as well as annual energy consumption. (The thermal performance of building elements with high thermal mass may depart from this simplistic model.) In a given climate, heating energy consumption approaches zero asymptotically as the thermal resistance of a building component is increased, but it is difficult, if not impossible, for a conventional insulated, opaque building element to become a net provider of energy to the building.

Windows and skylights are typically viewed as having very poor thermal insulating properties, an observation which is correct if a simple window is analysed on a cold winter night. However, windows have the unique property of becoming potential energy savers if available solar gain and daylight can be effectively harnessed. Thus, strategies for maximizing the energy efficiency of windows should balance attempts to minimize thermal losses with approaches which utilize the sun's heat and light. In this way the net annual performance can be optimized.

Within the constraint of this paper, we focus attention on the control of thermal losses from windows. Other important energy related performance issues such as solar control, daylighting and natural ventilation are addressed in other papers in this symposium. We consider here those strategies for minimizing the thermal losses from windows which permit desired solar heat gain and daylight to enter. The wide range of devices which satisfy these requirements can be further divided into two broad subsets: 1) intrinsic or static solutions, in which thermal losses are reduced by careful materials selection and construction of the window system, and 2) window management strategies, in which thermal losses are controlled by an operation which deploys an insulating element or in some other manner alters the window properties to reduce losses.

It is important to keep in mind the distinction between the rate of heat loss from a window (i.e. its U value) and its net annual energy performance. The observation that a conventional double glazed window, facing south, may collect more heat than it loses on an annual basis in many climates, does not reduce the requirement for a heating system which will compensate for the window heat loss on a cold winter night. In addition to reducing annual energy consumption, improved windows with very low thermal loss characteristics will provide the following benefits: 1) they will reduce the magnitude of peak building heating loads, 2) they will improve thermal comfort in the vicinity of the window, and 3) they will provide more architectural design flexibility by allowing east, west, and even north windows to provide net energy benefits, rather than losses.

1.2 HEAT TRANSFER RATES

Any discussion of thermal losses must center around a method for calculating or measuring those losses. We use the overall heat transfer rate, or U value, throughout this paper. The reader is reminded that the U value of a building component is not an intrinsic property of that element but rather a heat transfer rate which exists under carefully defined environmental conditions. The U value of the window is defined by:

$$U = \left(\frac{1}{h_o} + \frac{1}{C} + \frac{1}{h_i} \right)^{-1} \qquad (1)$$

where h_o and h_i are the outside and inside surface heat transfer coefficients respectively and C is the net conductance of the window system. In a complex window with accessories, C may be composed of several series and parallel heat transfer rates. Both h_o and h_i have convective and radiative components, and changes in wind speed and direction, surface emissivities, room and sky emissivities, room, air and sky temperatures and other factors will modify the values of h_o and h_i. In the case of a single glazed window, where the glass sheet has a high conductivity, virtually all of the insulating value is provided by the surface air layers. The U value of single glazing can thus fluctuate by $\pm$ 40% with large changes in h_o or h_i. For better insulated windows,however, the relative importance of the film coefficients diminishes, and the total U value becomes largely independent of h_o and h_i. Throughout this paper we use a value of .16 $m^2 \cdot K/W$ (.91 $hr \cdot ft^2 \cdot {}^oF/Btu$) for the combined thermal resistance of the two air films. This corresponds to h_i calculated for free convection on the interior glass surface and h_o based upon forced convection on the exterior surface.

2.0 SINGLE GLAZING

Although the U value of single glazing is relatively high, if the surface heat transfer coefficients can be modified, the nominal value of 6.25 $W/m^2 \cdot K$ (1.1 $Btu/hr \cdot ft^2 \cdot {}^oF$) might be reduced to the range 3.4 - 4.5 $W/m^2 \cdot K$ (.6 - .8 $Btu/hr \cdot ft^2 \cdot {}^oF$). Some techniques for reducing

h_o and h_i have been observed or proposed. These include screens and other external factors which reduce radiative and forced convective heat transfer (1-2,18), solar control films, transparent heat mirror films, or glass coatings which reduce interior surface emissivity and thus, h_i (3-5), and a large selection of shades, blinds, drapes and shutters which will reduce window thermal losses. Moveable insulating devices are discussed in the last portion of this paper.

3.0 DOUBLE GLAZED WINDOWS

Well managed, single glazed windows may be an acceptable, cost effective solution in mild climates. Our concern is the thermal performance of windows in more severe climates. Because of rising energy costs, consumer education and new building codes, double glazing is becoming common in new construction in much of the colder half of the United States. Double glazed units may be hermetically sealed using glass to glass seals or polymeric sealant systems, or they may be mechanically attached in a manner which allows removal of one of the glazing elements. In both cases, the improvement in thermal performance is due to the insulating effect of an enclosed air layer. Neglecting frame effects, the nominal U value of a double glazed window with a 2 cm (.79 in) air gap is 2.84 $W/m^2 \cdot K$ (.50 $Btu/hr \cdot ft^2 \cdot {}^oF$), or 55% less than the U value of 6.25 $W/m^2 \cdot K$ (1.1 $Btu/hr \cdot ft^2 \cdot {}^oF$) which characterizes single glazing. Although this is a substantial improvement over single glazing, a double glazed window will still transfer ten times the energy of a well insulated wall on a cold winter night. With an understanding of the heat transfer mechanisms which characterize thermal losses in double glazing, several options become apparent for reducing the net heat transfer rate. In a double glazed window under typical winter conditions, approximately two thirds of the heat transfer is due to radiation, with the remaining 1/3 from conduction/convection. We consider, first, approaches to reduce conductive and convective loss mechanisms, then techniques for reducing radiative losses, and finally, strategies combining both convection and radiation suppression.

3.1 CONDUCTIVE/CONVECTIVE HEAT TRANSFER

Convective heat transfer in vertical air spaces has been studied by a number of workers analytically and experimentally (6-12). Direct measurement of air space temperature gradients and heat transfer rates, and interferometric studies confirm that there are two flow regimes with differing heat transfer characteristics. In the range of temperature and height to thickness ratios H/L of architectural interest, the flow regimes depend upon the value of the Grashof number, Gr and the ratio H/L.

The "conduction regime" is characterized by a linear temperature drop across the central portion of the air space with heat transfer occuring by conduction only. Convective effects do occur at the upper and lower edges of the air space, and although they have only a small influence on the overall average rate of heat transfer, the higher localized rate of heat transfer at the lower edge will result in lower interior glass temperatures and increased chance of condensation.

Under conditions for which the Grashof number becomes large, heat transfer no longer occurs by conduction alone. The principal temperature gradients are concentrated in well defined boundary layers which form along the hot and cold glass surfaces. This is the so-called "boundary layer regime." There is a linear temperature gradient in the vertical direction through the central core of air but virtually no horizontal temperature gradient across the core and thus no conductive heat flow.

Conditions in which the core air layer shrinks and the boundary layers merge are referred to as the "transition regime." Heat transfer occurs by both conduction and convection in this regime.

The coefficients for convective heat transfer through an air space can be calculated from:

$$h_c = \frac{k}{L} Nu_L \tag{2}$$

where the Nusselt number, Nu_L is a dimensionless relation of the form

$$Nu_L = c(Gr_L)^m \left(\frac{H}{L}\right)^n \tag{3}$$

where k is the conductivity, Gr_L is the Grashof number, H is the height and L is the thickness of the airspace; c, m, and n are constants. The Grashof number is calculated from:

$$Gr_L = \frac{g\beta(T_H - T_C)L^3}{\nu^2} \quad (4)$$

where
- g: gravitational acceleration
- β: thermal expansion coefficient
- T_H, T_C: hot and cold glass temperature
- ν: kinematic viscosity

With $Nu_L = 1$, h_c takes on the familiar form of an equation for conductive heat transfer. An increase in Nu_L signifies the appearance of convective effects in the heat transfer rate.

3.1.1 SUBSTITUTE GASES

Most of the convective heat transfer studies referenced above have examined air as the fill gas. With a given gas or gas mixture such as air, the Grashof number and ultimately the heat transfer rate is a function of average gas temperature, temperature difference across the gap and gap size. Christensen et. al. have examined experimentally the details of heat transfer through air filled, unvented, idealized double glazing using hot box measurements (13). These data agreed reasonably well with interferometric data obtained by Eckert and Carlson (12) and earlier studies of the thermal insulating value of airspaces (11). Prior to the introduction of reliable sealed insulating glass units air was the only available choice as a fill gas. However, with durable hermetically sealed insulating glass, one can consider the option of replacing air with another gas which might reduce the conductive/convective heat loss rate.

An examination of the functional dependence of h_c provides an insight into the desirable gas properties needed to minimize conductive/convective heat transfer rates. In the conduction regime we require a gas with low conductivity to minimize the heat transfer rate. As long as we remain in the conduction regime, the heat transfer rate will drop as the air space thickness increases. The viscosity should thus be high to maximize the air space thickness at which the onset of convection occurs. In the selection of candidate gases other requirements such as cost and toxicity must be considered. These are discussed in more detail at the end of section 3.1.3.

A number of commonly available gases have properties which suggest they may reduce heat transfer rates if used as a fill gas. We have recently completed an analysis of six gases (CO_2, Argon, SO_2, SF_6, CCl_2F_2, and Kr) which appear to be likely substitutes for air. Similar analysis has been done in previously published studies (14-18), but most of these calculations utilize correlations for Nu derived from studies with air. In addition, there is considerable uncertainty concerning the critical Grashof number at which the transition from conduction regime to boundary layer regime occurs. Because of these factors the validity of results based upon calculations alone is open to question. (There is also uncertainty for air; see Ref 10, p. 158 and Ref 18, p. 264). Glaser has recently published a summary of the results of extensive hot plate tests of double glazing with different fill gases, gas mixtures, plate separations and low emissivity coatings (19). Although the tests were run at a single temperature difference and over a limited range of glass to glass spacing the extensive experimental data in reference 19 is preferable to results based upon analytical and semi-empirical correlations of questionable validity for gases other than air. We have thus used Glaser's reported results in many of the calculations which follow in this section.

Fig. 1 shows the net airspace conductance as a function of glass separation for uncoated glass with temperature difference of 10°C (18°F) with mean air space temperature of 10°C (50°F). Curves for krypton and vacuum are calculated and the remainder are drawn from data derived from Ref 19. Several patterns emerge from an analysis of the plots.

In very small gaps ($L < 1$ cm) (.39 in) the gases with lowest conductivity (CCl_2F_2, SO_2, Kr) show a distinct advantage over others. As the gap increases in size, these gases show little or no decrease in conductance and in some cases a slight increase in heat transfer rate, suggesting that h_c is already dominated by convection. The Grashof number for these gases lies in the boundary layer regime for even small gap sizes. The curves for air, argon, and CO_2, however, show a characteristic drop in h_c with increasing air space width, indicating that heat transfer is largely by conduction. The curves then rise or level out as the boundary layer regime is reached and convection begins to dominate.

3.1.2 IR ABSORPTION IN PARTICIPATING MEDIA

The net air space conductance plotted in Fig. 1 includes both radiative and conductive/convective heat transfer. With air as the fill gas, the two heat transfer mechanisms operate in parallel and the total air space conductance, h_a, may be obtained by adding the conductive/convective component, h_c, to the radiative component Eh_r. E is the effective emittance of the air space. Neglecting edge effects in the case of plane parallel plates, E is:

$$E = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \tag{5}$$

where $\varepsilon_1, \varepsilon_2$ are the plate emissivities. The radiative heat transfer coefficient h_r is:

$$h_r = 5.6697 \times 10^{-8} \ (T_1^2 + T_2^2)\ (T_1 + T_2) \quad W/m^2 \cdot K \tag{6}$$

where T_1, T_2 are plate temperatures, K. Note that under typical winter temperature conditions radiative transfer dominates h_c as shown by the curve for vacuum in Fig. 1 which illustrates the magnitude of the radiative term alone.

With air and other non-participating media, the convective and radiative heat transfer components can be added to obtain the total air space conductance, h_a.

$$h_a = h_c + Eh_r \tag{7}$$

However, with gases that have absorption bands in the long wave infrared region, the long wave radiation exchange can no longer be treated as an independent heat transfer path. This is seen clearly in Fig. 10a and 10b of Ref. 19, where Nu is plotted against $GrPr(L/H)^{1/3}$ for an airspace bounded by uncoated glass as well as for glass with a low emissivity coating. For gases with significant IR absorption bands, (SF_6, SO_2, CCl_2F_2) the Nusselt number for uncoated glass is lower than that for coated glass. Qualitatively, the apparent reduction in Nu is actually a reduction in the net radiative transfer caused by the IR absorption of the gases. The effect is not seen with coated glass because the very low emissivity coatings eliminate virtually all of the radiative exchange. From data in the referenced figure for SF_6, the Nusselt number in the uncoated glass case is approximately 20% lower than the coated glass. Since h_c accounts for about 1/3 of the total air space conductance for this case, the data suggest a reduction of about 6 - 7% in total air space conductance. This can be compared to a calculation of the effective air space emittance in the presence of a participating gas medium. It can be shown (20,21) that the effective air space emittance, E_A is given by

$$E_A \doteq \frac{1}{\frac{1-\varepsilon_1}{\varepsilon_1} + \frac{1-\varepsilon_2}{\varepsilon_2} + \frac{1}{1-\frac{\varepsilon_m}{2}}} \tag{8}$$

where $\varepsilon_1, \varepsilon_2$ and ε_m are the two glass emissivities and the effective gas emissivity respectively. In the case of an IR transparent gas ($\varepsilon_m = 0$) E_A reduces to the well known formula for air space emittance of a double glazed window. Eq 8 assumes that the gas - glass and the glass-glass view factors are both unity, which is reasonable for large window height to spacing ratios. Data obtained for SF_6 shows a deep absorption band in the center of a 300 K (81°F) black body emission spectrum, with nearly complete absorption from 10 to 12 microns (22). Because the radiation exchange involves the hemispherical properties rather than normal properties, equivalent mean hemispherical beam length is 1.8 times the air gap spacing. For SF_6 we estimate from Ref 22 that $\varepsilon_m = .2$ so that $E_A = .67$, a reduction of about 8% from the case of an air filled gap. Since the 8% reduction affects only h_r which is approximately 2/3 of the total air gap conductance, h_a, the net affect will be a calculated 6% drop in h_a. This compares to the 6-7% estimated from the data in ref 19.

3.1.3 GAS MIXTURES

In addition to measuring heat flow properties with different gases the measurement apparatus described in ref 19 was designed to allow the introduction of controlled gas mixtures. Results are given for air-argon, air-SF_6, and argon-SF_6 mixtures. As the ratio of gases is varied for the air-argon mixture, the conductance is a linear function between the two endpoints, for all argon, or all air. However, in the case of the argon-SF_6 mixture there is a distinct minimum conductance which shifts as a function of gap size.

A review of the results shown in Fig. 1 indicates that the air space conductance which is normally 4.90 $W/m^2 \cdot K$ (.86 $BTU/hr \cdot ft^2 \cdot °F$) for an optimim air filled gap can be reduced as much as 11% to 4.35 $W/m^2 \cdot K$ (.77 $BTU/hr \cdot ft^2 \cdot °F$) with the use of krypton as a fill gas. If the glass spacing is constrained to small dimensions, the relative improvement is larger. For a 1 cm gap (.39 in) the net air space conductance is 6.05 $W/m^2 \cdot K$ (1.07 $BTU/hr \cdot ft^2 \cdot °F$) for air and 4.58 $W/m^2 \cdot K$ (.81 $BTU/hr \cdot ft^2 \cdot °F$) for krypton, a 24% reduction. The reduction is overall window U value for the two cases discussed above is 7% and 14% respectively.

Although krypton and SO_2 provide the best improvements in thermal conductance, other factors must be considered in selecting alternatives to air. Any gas chosen should be non-toxic and environmentally acceptable, must not diffuse through or chemically attack window framing and sealant materials, must not be degraded by exposure to sunlight or UV, and must not condense in the air space when temperatures drop as low as -35°C (-31°F). Finally, the gas must be available in relatively large volumes at "reasonable" cost. Krypton, SF_6 and argon meet the first four requirements. Gas cost has been estimated from discussions with industrial gas suppliers for an insulating pane unit with 1 cm (.39in) separation. Krypton appears to be too costly at \$5.00/m^2 (\$ .47/ft^2). SF_6 and argon are considerably cheaper: \$ .48/m^2 (\$ .05/ft^2) for SF_6 and \$ .04/m^2 (\$.003/ft^2) for argon.

One must conclude that the replacement of air with other gases to reduce conductive/convective losses results in a noticeable but modest reduction in the gas space conductance. Since conduction/convection was identified as contributing only 1/3 to the gas space heat loss rate, these results are not surprising. The use of alternative gases will show the greatest improvement when other window design factors demand that the interpane spacing be small. Conversely, the performance of "wide" (approximately 2.5 cm or 1 in) air filled units may be equalled by much thinner double glazed units if gases other than air are used. The use of low conductivity gases in conjunction with IR reflective coatings on glass is discussed in a later section.

Before leaving the subject of reducing convective/conductive heat loss, we examine briefly two other related approaches based on partitioning the gas space and a third approach based upon partial evacuation of the air space.

3.1.4 PARTITIONED GAS SPACE

For a single air space, the minimum conductance is typically reached with an air space thickness of .6 to 2.0 cm. Once the boundary layer regime has been reached, further increases in air space thickness show little or no decrease in air space conductance.

However, if gas spaces are stacked in series with a physical divider between adjacent spaces, the net conductance h'_a of the double gas space is approximately one half of the single gas space conductance, h_a. We would actually expect to see $h'_a \approx .47\ h_a$ in the case of air because the temperature drop across each gas space is approximately one half of what it would otherwise have been for a single airspace and h_c is correspondingly less due to the smaller temperature difference. Triple glazed windows which incorporate two airspaces are by no means novel. Several different window frame and sash designs have evolved incorporating triple glazing. In each case the addition of a third glass layer imposes a weight penalty on the window and therefore requires additional frame and sash structure and stiffness, particularly if the sash is to be operable.

An alternative design, shown in Fig. 2, may be capable of achieving roughly equivalent thermal performance with little or no increase in window weight and perhaps with reduced first cost compared to conventional triple glazing. In this design a thin, vertical, optically clear plastic film is utilized to partition the air space. For this application an "ideal" plastic layer would behave like glass with respect to long wave infrared radiation. Typical thin plastic films that we have considered are IR transmitting to varying degrees. This has no impact on their ability to act as a physical barrier between air spaces but it does reduce their thermal effectiveness due to the long wave radiation they transmit. Fig. 2 shows the U value performance range of typical multiple pane windows. The U value is shown for conventional double glazing (Fig.2a), conventional triple glazing (2b), two sheets of glass with a single plastic film insert (2c), and two sheets of glass with a double plastic film insert (2d). The range in U value shown for each design results from differing fill gases and gas space widths.

The double glazed windows with single and double plastic film inserts perform better than double glazing but no better than triple glazing. If the IR properties of the plastic films could be altered the performance would be improved, as shown by the "ideal" case, Fig. 2e. This approach to thermal control has two advantages. The improvement in thermal performance is achieved with virtually no increase in weight or structural requirements. In addition, using gases which have low conductance at small gap size, several very thin air spaces can be stacked to increase the total thermal resistance with a minimal overall glass to glass spacing. If non sealed double glazing is used with air as the fill gas, equivalent thermal resistance can still be achieved if the constraint on window glass to glass spacing is relaxed. Although the introduction of multiple layers of thin plastic films creates several new performance requirements, it has little impact on several key elements of insulating glass design. As windows of this type are not commercially available, the comments which follow must remain speculative. The following discussion assumes a sealed glass window unit with a gas fill, but most of the comments apply equally to a non sealed double glazed system where the plastic film insert might be removable.

Thin plastic films (.0013-.013 cm (.0005-.005 in.)) would be stretched over metal or plastic frames and glued, sealed or mechanically locked in place. The frame with one or two plastic layers would then be inserted within the insulating glass assembly, just prior to sealing the glass unit. Although the sealed glass unit must be impermeable to the gas fill, the plastic layer(s) within the unit need not be gas tight, allowing a single fill point to circulate gas throughout the layers, and allowing equalization of any pressure differentials within the glazed unit.

The plastic film must be stretched properly, preferably with tension to reduce or eliminate sag which would result from thermal expansion as the unit heats up. The film must resist degradation resulting from exposure to sunlight in the presence of the fill gas and any other vapors resulting from the glass sealants. Two plastic films that have good resistance to solar exposure and demonstrated performance in window and solar energy applications are polyethylene terephthalate (PET) and fluorinated ethylene propylene (FEP). Due to its high index of refraction, PET reflects 12% of the incident energy from both surfaces at normal incidence. A double layer of PET would thus lose 23% of the incident energy and light by reflection alone. This property may also reduce acceptance in a building due to the brighter internal reflections that will be perceived by building occupants, particularly on overcast days. It is possible to substantially reduce these reflection losses by depositing a very thin anti-reflection coating on both sides of the plastic film. Although this would be prohibitively expensive now, high rate film deposition processes may soon make it possible to apply such coatings at $.05 per square foot per surface (23). FEP has a much lower index of refraction (1.34) and transmits 96% of the normal incident solar energy. Although its optical clarity and mechanical properties are not as good as PET, it has exhibited excellent durability over long time periods under exposure to sunlight. It does have substantial transmission in the long wave IR which reduces its effectiveness slightly compared to polyester.

The use of multilayer, highly transparent, thin plastic films has already attracted attention in solar collector and passive solar heating applications with several materials available or under development (24,25). It appears that the same approach to heat loss reduction in windows is promising. Although we are optimistic about the ultimate introduction of more sophiscated IR reflective coatings as discussed in section 3.2, we conclude that very low conductance windows might be fabricated using double glazed windows with one or two simple plastic film layers within the unit to create a series resistance to heat flow.

3.1.5 CONVECTION SUPPRESSION SLAT SYSTEMS

A second major approach to reducing convective heat loss employs a series of horizontal partitions located within the air gap of an insulating window pane. This approach suppresses convection by reducing the Rayleigh number which characterizes the small air space below the critical value at which the onset of natural convection occurs. If convection can be supressed, the thermal resistance of the airspace in the conduction mode becomes a monotonic increasing function of window crossectional thickness. Convection suppression using honeycombs has been studied extensively in order to reduce heat loss from horizontal or inclined flat plate solar collectors. In these applications, reductions in solar gains typically have negated any observed reduction in upward heat losses. Because maximizing solar gain is not as critical in windows, modified honeycomb approaches for convection suppresssion may hold promise in window applications where optical clarity is not essential.

Berlad et. al. have proposed and studied (26) a window system which effectively suppresses convection within the air gap by segmenting the air space into thin horizontal air cells with an insulating slat system (Fig. 3a). The horizontal slats can be retracted out of the airspace like a venetian blind, and can be tilted and closed for sun control and privacy. The slats have a low emissivity coating so that infrared coupling of the two window panes is partially supressed when the window system is in the "open" mode. Infrared decoupling is achieved in the "closed" mode. When closed, the nonrectangular parallelepiped crossection forms a thick internal insulating barrier (see Fig. 3b). Measurements of heat transfer rates and interferometric studies of optimal convection suppression designs are in progress. Results to date have demonstrated an air space thermal conductance of .85 $W/m^2 \cdot K$ (.15 $Btu/hr \cdot ft^2 \cdot {}^\circ F$) for the blinds in an open mode and .51 $W/m^2 \cdot K$ (.09 $Btu/hr \cdot ft^2 \cdot {}^\circ F$) in the closed mode. If further studies support these initial results and practical design and manufacturing problems can be resolved in a cost effective manner, this approach could find acceptance whenever very low window thermal conductance is required.

3.1.6 PARTIALLY EVACUATED AIRSPACES

In the field of solar collector design, partial evacuation of the air space between the absorbing surface and transparent cover has been utilized to reduce thermal losses (27). We examine this approach to determine if it is applicable to insulating window designs.

Over a large range of gas pressure below one atmosphere, the thermal conductivity of simple gases is constant. This relation holds until the pressure of the gas is reduced so low that the mean free path of gas molecules becomes greater than the air space dimension. As the pressure is first reduced from one atmosphere, convective losses will decrease and the air space conductance levels off at a value determined by the gas conductivity and the air gap dimension. For a 1.22m (48 in.) high window with three different air gaps, the conductance due to convection and conduction is shown as a function of the air space pressure in Fig. 4.

Note that the critical pressure at which convection is suppressed varies with L/H as we would expect. With the given parameters, the 1.27 cm (.5 in.) air space has virtually no convective component at a pressure of one atmosphere. To reduce the heat transfer rate below the conduction plateau shown in Fig. 4 requires a further substantial reduction in pressure. For air, the mean free path is given approximately by 5/P where P is the pressure in mtorr (28). The air gap pressure must thus be reduced to the range 1-5 mtorr before the conductivity begins to drop.

The effects of pressure reductions with alternate gas fills were examined and yielded qualitatively similar results. Before pursuing this approach further we must question the practical feasibility of constructing windows with reduced pressures in the gaps. Evacuated solar collectors have taken two forms; cylindrical forms and flat plates with spacers. The cylindrical form is inherently resistant to the pressure forces but does not have acceptable optical properties for window applications. The spacers required with flat plate systems resist the inward pressure forces but create visual interference as well as constituting a conduction heat leak. The forces which must be resisted are substantial. To suppress convection in the case of the 2.54cm (1 in.) air gap, the pressure differential across the glass is approximately 5.5 x 10^4 Pa (1150 lbf/ft^2). Vacuum integrity, lifetime, and costs are all significant practical obstacles and safety, in the event of a catastrophic failure, would be an additional concern. We conclude that a reduction in air gap pressure to suppress convection does not represent a viable approach to reducing air gap thermal losses in windows.

3.2 HEAT MIRROR COATINGS

Although several of the approaches to reducing heat transfer rates in double glazing look promising, truly significant reductions in heat transfer rates will be achieved only when radiative losses are reduced. If all conductive and convective losses were totally eliminated, radiative transfer would limit the minimum U value to about 2.3 $W/m^2 \cdot K$ (.4 $Btu/hr \cdot ft^2 \cdot {}^\circ F$) for double glazing. (See Fig. 1). One approach to reducing the radiative component of thermal losses while maintaining high solar transmission involves the use of thin, transparent optical films which are reflective to the long-wave infrared radiation emitted by room temperature surfaces (Fig. 5). These low emittance films known as "heat mirrors," can be applied to glass or plastic glazing materials. Building designers already specify heat mirror products in the form of some types of reflective glass and sun control plastic films, commercially available products which in addition to reducing solar gain, also reduce winter thermal losses by varying amounts. However, since both products were developed to provide sun control functions, their reduced solar transmittance makes them generally unsuitable for applications in which winter solar gain and daylight is desirable.

Heat mirrors may be deposited on plastic or glass substrates using different deposition processes depending on the materials selected. Two basic materials systems are used; metal-dielectric multilayers and semiconductor coatings. Multi-layer coatings utilize a metallic layer (such as copper, silver or gold) reflective to the infrared and one or more dielectric layers as antireflection layers to improve visible transmittance and increase durability. Multi-layer heat mirrors can be produced by a variety of thin film deposition processes such as thermal evaporation and sputtering. Single layers of some doped semiconductors are intrinsic transmitters of shortwave energy but are reflective to long-wave infrared. Semiconductor type heat mirrors have been produced primarily by high-temperature pyrolysis processes which has restricted their use to glass substrates, although some are now being produced at lower substrate temperatures using sputtering processes. Material systems and deposition processes for both approaches are reviewed in more detail in Ref. 18, 29-35.

Transparent heat mirrors which are deposited on plastic have the capability of being applied on the interior surface of single glazed windows, thereby reducing the U value from 6.25 $W/m^2 \cdot K$ (1.1 $Btu/hr \cdot ft^2 \cdot {}^oF$) to approximately 3.98 $W/m^2 \cdot K$ (.7 $Btu/hr \cdot ft^2 \cdot {}^oF$). One fundamental problem with this type of application is that it subjects the optical coating to substantial environmental stress--primarily abrasive and corrosive assaults due to cleaning, finger prints, and pollutants from normal activities in a house or office. If the optical coating does not have sufficient inherent stability, it may be further protected with a vacuum deposited or chemically applied overcoat, a protective laminate or it may be deposited directly on an IR transparent substrate which is then glued to the window, coating side toward the glass. Although each of these approaches shows some promise, none appears to offer a fully satisfactory solution at this time.

Heat mirrors deposited directly on glass are typically more durable than equivalent coatings on plastic 1) because of the greater freedom in deposition conditions (higher allowable substrate temperature, etc.), 2) because of the relatively inert and impervious nature of the glass substrate compared to plastic films, and 3) because of the substrate rigidity and hardness. If coatings are applied to glass with vacuum deposition or sputtering processes as they are now, substrate handling requirements raise the projected cost above that of roll coating plastic. However, there is considerable effort underway to develop film deposition techniques that are integrated with the glass manufacturing process and occur at atmospheric pressure, eliminating the requirement for costly vacuum chambers.

If heat mirrors applied to plastic films are not sufficiently corrosion and abrasion resistant to withstand direct exposure, they will still find other window applications with less severe requirements. The retrofit function could still be utilized if the heat mirror was used in conjunction with any of the many interior storm window retrofits now on the market. These usually consist of metal or plastic framing system with a glazing of thin plastic film, rigid plastic sheet or glass. These can be installed on a seasonal or permanent basis, and can cover the existing glass only, the existing sash elements, or the entire window opening. By creating an air space as well as reducing radiative exchange the heat transfer rate may be reduced to as low as 2.0 $W/m^2 \cdot K$ (.35 $Btu/hr \cdot ft^2 \cdot {}^oF$). Air leakage may reduce the thermal effectiveness and condensation within the air space is a problem which must also be addressed.

The double glazed window market offers a safer application for heat mirrors deposited on glass or plastic. Heat mirrors could be incorporated into new windows in the factory under better handling conditions than in field retrofit situations. Directly coated glass could be used or the plastic films could be cut and applied to glass as the window was assembled. As a component in a new window the product lifetime becomes important. Coatings on glass appear to have an advantage over those on plastic, as the plastic film and adhesive introduce further uncertainty into the determination of effective heat mirror lifetime. Good quality double glazed windows should last 20-50 years, and in many cases much longer. It appears unlikely that one could guarantee a heat mirror/plastic film/adhesive lifetime of greater than 10-20 years. This suggests either that coated glass be used in sealed insulating glass units or that windows incorporating heat mirrors on plastic films allow for future replacement of the plastic film.

Conceptual designs of such a window are now undergoing more intensive study. These are similar in design to the vertical convection suppression barriers discussed previously. Several variations are shown in Fig. 6. The first is a conventional double glazed window. If the glass is coated directly a sealed insulating unit might be used. If the heat mirror is deposited on a plastic substrate, the plastic would then be laminated to an interior glass pane which is removable, a standard window design. With the sealed unit a low conductivity gas may be used in the air space, resulting in a U value as low as .9-1.0 $W/m^2 \cdot K$ (.16 - .18 $Btu/hr \cdot ft^2 \cdot {}^oF$). As one would expect, the low conductivity gas provides a proportionately larger reduction in U value (about 35%) in the case where radiative exchange is suppressed compared to the modest reduction of about 10% in a unit with uncoated glass.

A more interesting design incorporates the coated plastic film stretched over a frame and mounted in the middle of the window air space. This configuration produces two air gaps and if a single coating is deposited on PET plastic a U value of 1.19 $W/m^2 \cdot K$ (.21 $Btu/hr \cdot ft^2 \cdot {}^oF$)

can be obtained. The sash and frame would be designed to allow the heat mirror insert to be removed and replaced at appropriate intervals. The use of a sealed glass unit with low conductivity gas might drop the U value to .87 W/m^2·K (.15 Btu/hr·ft^2·°F). Note that the calculations in Fig. 6 indicate that for the same configuration, but with the heat mirror on the number 5 surface, the U value is lower than the corresponding case with the heat mirror on one side of the film due to IR absorbtion in the plastic. In this case the IR absorbtance of the plastic acts as a resistance to radiative transfer.

A further variation of the same concept would wrap the coated plastic around both sides of a metal or plastic frame insert. In this configuration, three airspaces are created. With a single coated heat mirror, two air spaces see the coating directly while the airspace formed between the two plastic layers will still have a low net emittance if IR transparent plastic is used, or if very thin PET is used. The net result is a window assembly with very low U values and no requirement for daily management or operation. Note that if a large crossection is acceptable, the case with a 3.8 cm (1.5 in) gap filled with air produces a calculated U value less than .5 W/m^2·K (.09 Btu/hr·ft^2·°F). Such a window will have a normal solar transmittance of .42 to .58 depending upon specific heat mirror properties. Those transmission losses which occur by absorption rather than reflection will partially offset thermal losses, and thus are not true losses. At large angles of incidence, reflection losses become more severe. Studies are underway to determine net system performance in several different climates to determine if the very low U value more than compensates for increased reflection losses.

Although results in the upper portion of Fig.6 include measured data, the calculated results in the lower portion await experimental validation. The infrared transmission of multiple layers of PET or other material used as the plastic substrates has a major impact on the calculated results and as it is not a definitive quantity, the experimental results might be expected to vary somewhat from the calculated values. Results for the simpler systems show agreement among various workers to about ± 15%. The expected accuracy of calculations for the multiple substrates would contain a greater potential error. These results therefore are presented as illustrative of the performance range of these window designs, rather than as definitive product performance values.

One concludes that there are several design options incorporating heat mirrors which have the potential for reducing the window U value below 1 W/m^2·K (.18 Btu/hr·ft^2·°F) and some which might achieve .5 W/m^2·K (.09 Btu/hr·ft^2·°F). Further analysis may indicate that the lower range is actually "overkill" and that even north windows may provide net energy benefits with such low U values. Efforts are underway to build and test such prototypes to determine if their actual performance meets expectations. Although several thermal shutters can provide a .5 W/m^2·K (.09 Btu/hr·ft^2·°F) heat loss rate, these windows incorporating hear mirror films are static units without the requirement for management actions and thus would be an important and impressive window option to have available for use in architectural design.

4.0 INSULATING SHUTTERS/MOVEABLE INSULATION

Shutters are a traditional form of window protection from climatic extremes and other undesired intrusion. Most shutters that one sees today are inoperable and serve an esthetic function only. However, concern with energy costs has seen interest in these devices rapdily rise and a number of types of operable shutters are now being manufactured or imported from overseas. Moveable insulation is of interest because it provides effective approaches to the retrofit of existing single and double glazed windows, as well as for new construction.

Moveable insulating devices come in all shapes and sizes. Shurcliff (37) has identified over 100 schemes for insulating windows and the inventive reader can no doubt add to the list. Most thermal insulators, however, have some common characteristics and a common set of potential flaws. An insulating layer (rigid board, flexible batt, multilayer films, granular materials, etc.) reduces heat loss associated with conductive, convective and radiative flows and mass transfer. The insulating layer may be located in three positions relative to glazing: internal, external, or between glass. When not in use, the insulating material slides, rolls, collapses, folds, or is otherwise removed from the window. Control and deployment of the devices may be initiated by automatic or manual means. "Shutters" as used in this context include blinds, shades, and drapes, and frequently provide solar control as well as thermal control. In addition these devices may fulfill the need for privacy, security, and aesthetics. We restrict our discussion to those devices designed primarily to reduce winter thermal losses. This subset of window management products may thus be seen as competitors or alternatives to the highly insulating glazing options discussed earlier.

Several important issues arise in any discussion of insulating shutters. They are identified briefly below:

1) Condensation

Insulating shutters placed on the interior will reduce glass temperatures and increase the likelihood of condensation. The magnitude of this effect will depend in part on the degree of air leakage around the insulating device and the tightness of the prime window.

2) Infiltration/Air Leakage

Infiltration through poorly fitting windows is a major energy loss factor in many buildings. Tight fitting shutters will reduce this loss substantially. Significant air leakage around the edge of the insulating shutter may negate the nominal insulating value of the device. Since most of these devices have extensive moving surfaces, seals and air leakage at the edges will be critical design problems.

3) Overheating

Many insulation devices may be left in place or utilized year round. If the device seals to the window effectively, overheating may occur when the sun strikes the window with the shutter closed. Unless provision is made to vent the heat buildup, both the shutter and window and all adjacent components must be designed to withstand the resultant high temperatures without failure or degradation.

4) Fire Safety

Many moveable insulating devices incorporate substantial quantities of plastic foams, plastic films and synthetic fibers. If used improperly, these may constitute a smoke and fire hazard.

5) Operational Reliability

Although many moveable insulating devices might be automated and motorized, cost constraints make it unlikely that single windows will be operated in this manner. Thus if potential savings are to be fully realized, insulating devices must be closed and opened conscientiously. The degree of user responsibility is critical because a fixed permanent solution with lower thermal resistance will perform better than a a device with higher thermal resistance which is deployed only occasionally. One solution is to couple the deployment of the thermal insulating device with an action that will be routinely taken to achieve thermal comfort or privacy. For example, if the rollup shade that is pulled to provide privacy as the sun sets is also designed to provide good insulating qualities, the thermal benefits will accrue on a regular basis. Effective energy conservation will be promoted and accelerated by coupling new thermal control functions to existing habits and lifestyles wherever possible.

6) Thermal Comfort

Like any other window with good insulating properties, if air leakage is reduced and interior surface temperatures rise, thermal comfort will be increased, particularly in the vicinity of the window. A draft free environment with higher mean radiant temperature will allow equivalent thermal comfort to be achieved at correspondingly lower air temperatures, resulting in additional energy savings.

7) Energy Savings

Moveable insulating devices used in conjunction with single or double glazed windows can reduce instantaneous thermal losses to a level characteristic of a well insulated wall while still collecting useful solar gain during the day. Studies are underway to assess the optimal level of moveable insulation required in different climates. In Fig. 7 we show the savings resulting from the use of moveable insulating devices with three levels of thermal resistance. The annual heating load is calculated for a 112 m^2 (1200 ft^2) house in Minneapolis with a window/floor ratio which varies from 0 to .40, and a basic envelope heat loss including infiltration (but without windows) of 49.1 $kJ/DD{\cdot}m^2$ (7.8 $Btu/DD{\cdot}ft^2$). The calculations were made with a large building energy analysis computer program (DOE-1) which has been modified to simulate the operation of moveable insulation. The insulation in this analysis covers the window from 6pm to 6am, although the computer program allows any schedule to be utilized. In each case the "R" value shown is the resultant "R" after the device is added to the existing window. From the data shown in the figure, single glass, even with an R1.76 (R10) shutter, shows higher losses as glass area is increased although very substantial savings compared to the use of single glass without the insulators. The net thermal loss of double glazing remains constant with increasing glass area for an R.53 (R3) shutter and with any further improvement in shutter thermal resistance, increasing glass area results in lower net loads. For this case study, each square foot of glass is collecting on the average 1.25 x 10^6kJ/m^2·yr (110,000 Btu/ft^2·yr). If the window area, which had been evenly distributed on all four elevations, is shifted so that 50% faces south, 20% each east and west and 10% north, additional savings are realized as shown in the figure. Finally, one should note that the incremental savings for improving shutter performance from R.88 (R5) to R1.76 (R10) is quite small, suggesting that U values below 1.14 W/m^2·K (.2 Btu/hr·ft^2·°F) provide only marginal returns particularly if some thermal loss is offset by useful solar gains. A more detailed study is underway to determine the marginal value of increasing the thermal resistance of insulating shutters.

The discussion of moveable insulating devices will end on a note of caution and optimism. Results of the single case study shown in Fig. 7 cannot be easily generalized or extended. These results may change when cooling loads are factored in. Furthermore, although the computer generated data has been extensively cross checked for consistency, experimental validation of results of this type must be completed to support the analytical work. Design and construction of an outdoor testing facility for evaluation of the comparative thermal performance of windows with moveable insulating systems is well advanced (38).

5.0 AIR FLOW WINDOWS

In a study of combined losses from double glazing due to temperature differences and infiltration, Bursey and Green (39) noted that in an exfiltration mode, the window may act as a counterflow heat exchanger with resultant reductions in effective U value. Several window systems which are sold in Europe capitalize upon this effect by intentionally forcing room air through the gap between the inner glazing and the outer single or double glazed unit (40-42). At moderately high flow rates (50 m^3/hr per meter width or 10 cfm per foot width) the effective U value is reduced to approximately .5 W/m^2·K (.09 Btu/hr·ft^2·°F). The air flow may be exhausted to the outside of the building or returned to the building HVAC system. In summer, the air flows over a set of venetian blinds in the air gap, carrying the absorbed heat outside and providing very low shading coefficients. Heat gain removed from the blinds in winter may be transferred to other parts of the building or directed to thermal storage. These systems have the added advantage of raising the glass surface temperature and thus improving thermal comfort. Perimeter heating systems can often be omitted, resulting in first cost savings which may pay for the air flow window system.

For all its advantages, the window performance must be considered in the context of overall building performance. If the room air was to be dumped without heat recovery, the air flow window would be a wise selection. But if an efficient heat recovery system was considered as an alternative, the enthalpy in the exhaust air might be better recovered by a central heat exchanger rather than the air flow windows. It remains to be seen in specific case studies which of these alternatives is the more efficient. Air flow windows do, however, provide yet another option for energy conservation through window management.

6.0 SUMMARY AND CONCLUSIONS

This paper has briefly reviewed the role of windows in energy efficient buildings. If undesired thermal losses can be minimized, desired solar gain and daylight from the windows will provide net energy benefits to the building. Although double glazing cuts heat losses from single glass by approximately 50%, there are other options which are capable of reducing single glazed window losses by over 90%. An examination of the heat transfer mechanisms in double glazing provides a starting point for reducing both convective and radiative losses. Different fill gases, air space baffles for convection suppression and partial evacuation offer approaches to reducing convective losses. However, since radiation is the dominant heat loss mode, heat mirrors (long wave infrared reflecting coatings) must be used to reduce radiative transfer in order to achieve very low heat transfer rates. A number of different window configurations are presented with both analytical and experimental data. Static window designs incorporating no moving elements with U values less than .5W/m^2·K (.09 Btu/hr·ft^2·°F) appear to be feasible. With U values at this low level the diffuse solar gain from the sky alone would allow even north facing windows to become net gainers of energy in many climates.

Moveable insulating devices offer a vast range of options and potentially provide very low U values. However, to work effectively they must be deployed and retracted on a regular basis. The best approach for guaranteeing effective operation is to couple the insulating function with a device and function that is already familiar and routine--such as closing a drape for privacy at night.

Although the focus of this technical discussion has been thermal performance, a major issue for maximizing energy savings is cost effectiveness. As products of the type described herein are developed for the market, tradeoffs are inevitably made between thermal performance requirements and manufacturing constraints designed to ensure durability and cost effectiveness. Final product specifications and performance are thus based on a compromise between that thermal performance which is technically obtainable and the realities of manufacturing processes, and product lifetime and cost. Double glazed window systems incorporating heat mirrors and low conductivity gases are commercially available in Europe, and thus form a bridge between the less sophisticated products commonly available today and the more speculative products described in this paper.

Two important simplifying assumptions have been used throughout this discussion. We have ignored infiltration effects in windows and the effect of window sash and frame elements. Both may seriously degrade expected window thermal performance if not adequately treated. Reductions in heat loss rates through glazed areas must be accompanied by design improvements aimed at reducing sash and frame losses as well as air leakage rates.

Undesired thermal losses and gains attributable to windows account for approximately 5% of total national energy consumption. If a selection of windows with improved thermal performance is available to be incorporated into buildings designed with a new energy conservation ethic, we could reasonably expect that a substantial fraction of those energy losses might be recovered. Benefits will accrue to the building occupants in the form of improved thermal comfort, to building owners and operators due to reduced energy costs and to the country, which can be made less dependent on environmentally and politically sensitive energy supplies.

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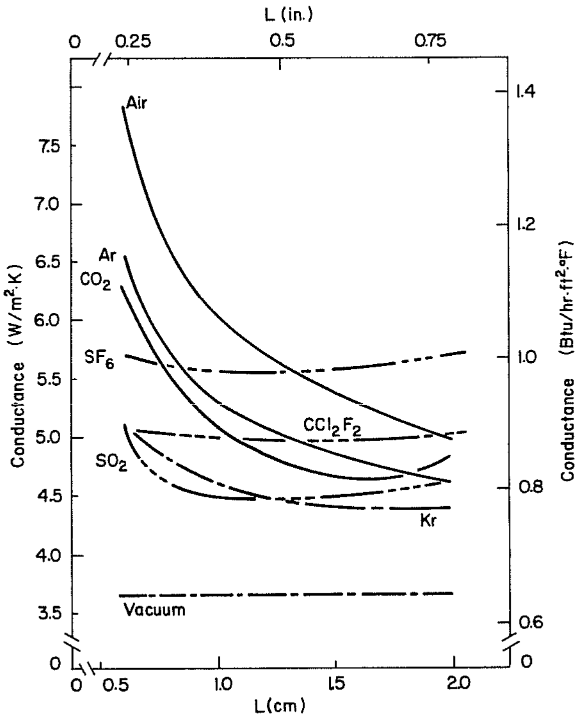

Fig. 1: TOTAL GAS SPACE CONDUCTANCE VS. GLASS SEPARATION FOR DOUBLE GLAZING WITH ΔT = 10°C (18°F)

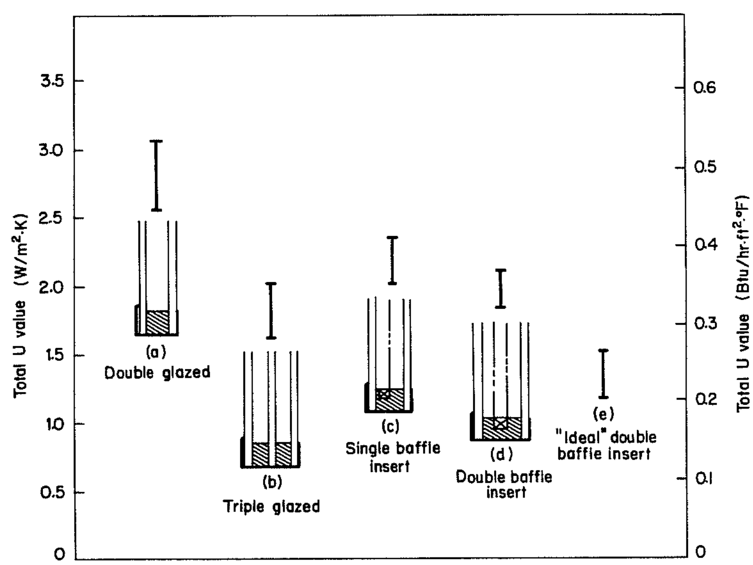

Fig. 2: U VALUE OF MULTIPLE GLAZING SYSTEMS. HEAT TRANSFER RATES OF CONVENTIONAL DOUBLE AND TRIPLE GLAZING, (a AND b), ARE COMPARED TO A DOUBLE GLAZED UNIT WITH SINGLE (c) AND DOUBLE (d) PLASTIC BAFFLE INSERTS, AS DESCRIBED IN THE TEXT. THE "IDEAL" DOUBLE INSERT (e) WOULD USE A COMPLETELY IR OPAQUE PLASTIC FILM

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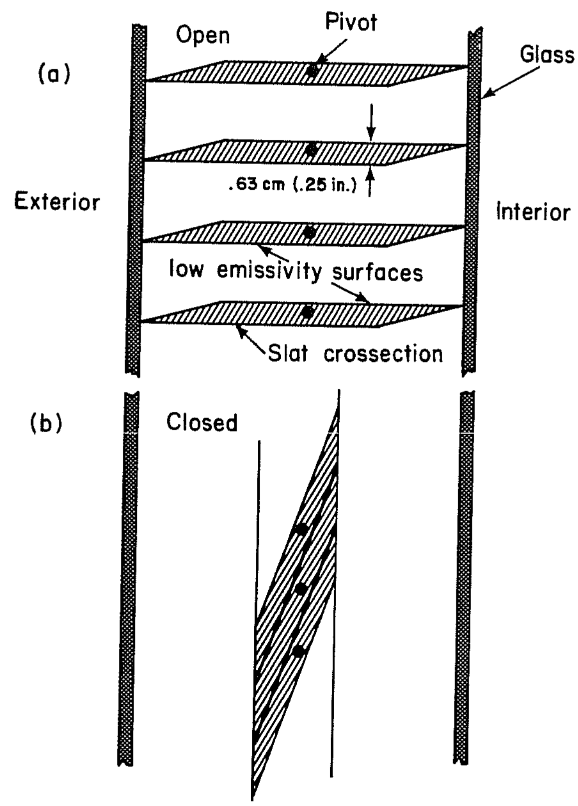

Fig. 3: SCHEMATIC DIAGRAM (CROSSECTION) OF CONVECTION SUPPRESSION INTERPANE SYSTEM (FROM REF 26)

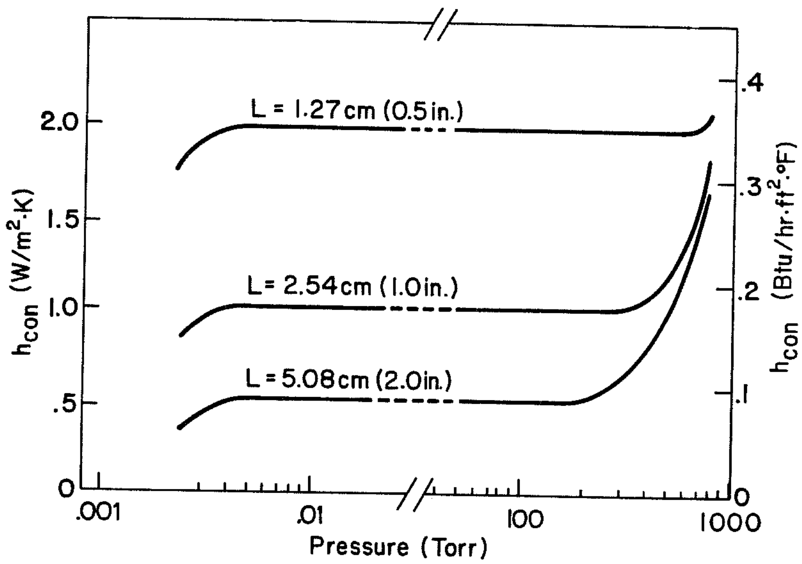

Fig. 4: AIR GAP CONDUCTANCE DUE TO CONVECTION AND CONDUCTION AS A FUNCTION OF PRESSURE WITHIN THE GAP

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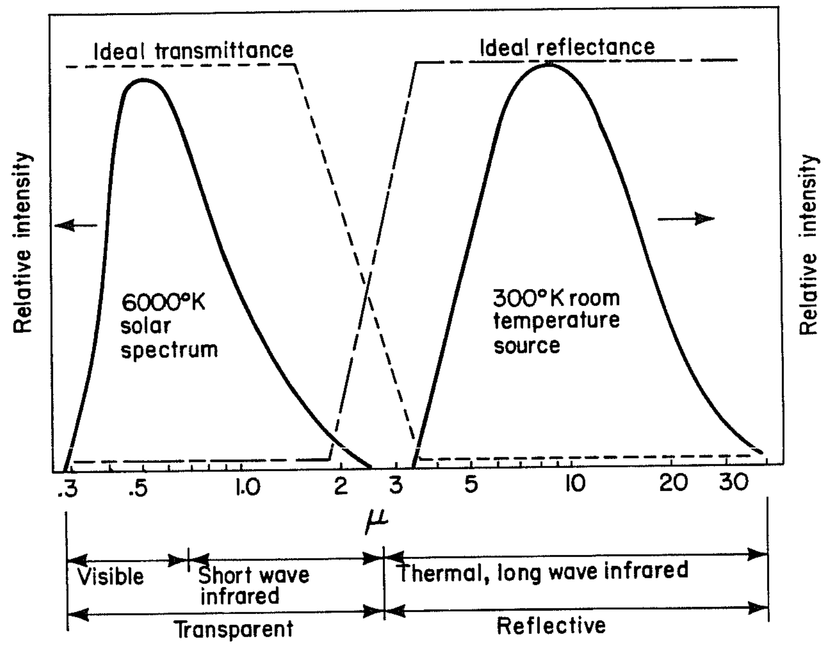


Fig. 5: IDEAL HEAT MIRROR SPECTRAL PROPERTIES

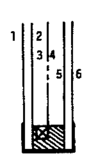
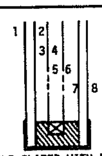
	TOTAL GAP (cm)	ε	SURFACE	GAS	ΔT (K)	SOLAR TRANSMITTANCE	U (W/m²·K)	CALCULATED OR MEASURED	SOURCE (Ref)
 DOUBLE GLAZED WINDOW	.6	.065	3	Air	10	--	2.7	meas.	Glaser (19)
	1.2	.065	3	Air	10	--	1.8	meas.	Glaser
	1.2	.065	3	Krypton	10	--	1.0	meas.	Glaser
	1.6	.065	3	Air	10	.45 visible (est	1.6	meas.	Glaser
	2.0	.1	3	Air	20	.37 visible	1.5	calc.	Karlson & Ribbing (34)
	1.2	.15	3	Air	--	--	1.9	calc.	Railio (16)
	1.27	.20	3	Air	22	.70	1.99	calc.	(ASHRAE Data)
	1.27	.05	3	Air	22	.63	1.70	calc.	(ASHRAE Data)
	1.2	.06 (est	3	Low Cond	--	.15-.49	1.4-1.5	meas.	Flachglas literature
	.64 - 1.27	low	3	Air	22	.04-.3	1.7-2.8	meas.	Commercially Available
	1.2	.1-.2	3	Krypton	19	--	.9	calc.	Kostlin (14)
	1.27	.05	3	Krypton	18	--	1.18	calc.	Silverstein (18)
 DOUBLE GLAZED WITH SINGLE PLASTIC INSERT	3.8	.20	3,4	Air	--	.59	.89	calc.	Johnson (36)
	2.54	.05	4	Air	10	.56	1.19	calc.	
	1.8	.05	4	Air	10	.56	1.43	calc.	
	1.8	.05	4	Argon	10	.56	1.33	calc.	
	1.8	.05	4	Krypton	10	.56	.87	calc.	
	1.8	.20	4	Air	10	.63	1.60	calc.	
	2.54	.05	5	Air	10	.50	1.01	calc.	
	1.8	.05	5	Air	10	.50	1.25	calc.	
	1.8	.05	5	Argon	10	.50	1.15	calc.	
	1.8	.05	5	Krypton	10	.50	.72	calc.	
	1.8	.20	5	Air	10	.56	1.52	calc.	
 DOUBLE GLAZED WITH DOUBLE PLASTIC INSERT	3.8	.05	7	Air	10	.46	.49	calc.	
	1.8	.05	7	Air	10	.46	1.24	calc.	
	1.8	.05	7	Argon	10	.46	.97	calc.	
	1.8	.05	7	Krypton	10	.46	.64	calc.	
	3.8	.05	3,6	Air	10	.42	.44	calc.	
	1.8	.05	3,6	Air	10	.42	1.24	calc.	
	1.8	.05	3,6	Argon	10	.42	.96	calc.	
	1.8	.05	3,6	Krypton	10	.42	.61	calc.	

Fig. 6: HEAT MIRROR CHARACTERISTICS AND REPRESENTATIVE THERMAL PERFORMANCE VALUES FOR SEVERAL WINDOW DESIGNS

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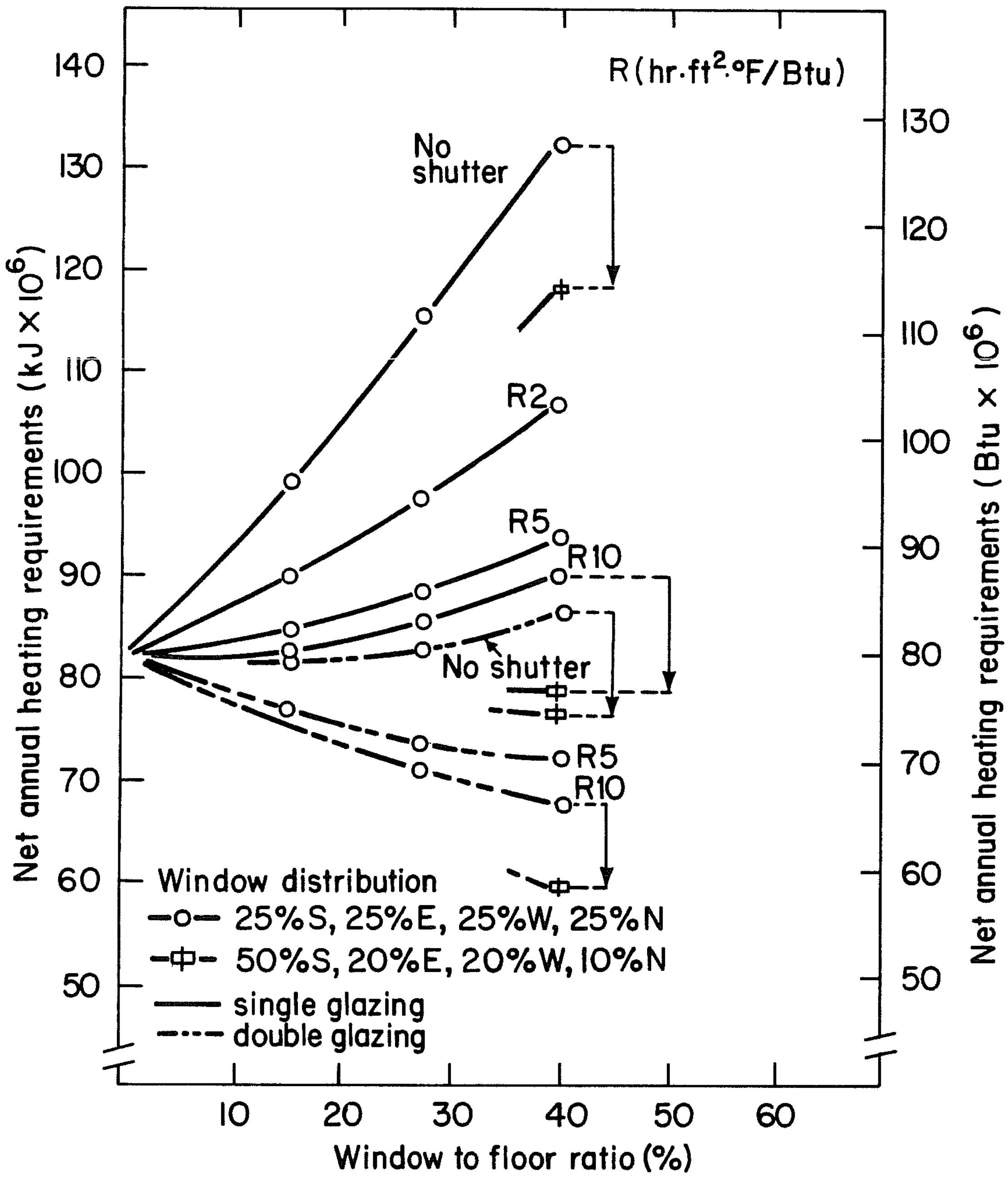

Fig. 7: NET ANNUAL HEATING ENERGY REQUIREMENTS FOR A 112 m^2 (1200 ft^2) HOUSE IN MINNEAPOLIS AS A FUNCTION OF WINDOW AREA AND GLAZING/ SHUTTER CHARACTERISTICS. SHUTTERS ARE DEPLOYED FROM 6 pm to 6 am

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